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Production and Delivery Policies for Improved Supply Chain Performance

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1. Introduction

The research on supply chain management evolved from two separate paths: (1) purchasing and supply perspective of the manufacturers, and (2) transportation and logistics perspective of the distributors. The former is the same as supplier base integration, which deals with traditional purchasing and supply management focusing on inventory and cycle time reduction. The latter concentrates on the logistics system for effective delivery of goods from supplier to customer. Supply chain management focuses on matching supply with demand to improve customer service without increasing inventory by eliminating inefficiencies and hidden operating costs throughout the whole process of materials flow. An essential concept of supply chain management is thus the coordination of all the activities from the material suppliers through manufacturer and distributors to the final customers. Recently, many researchers (for example, Weng, 1997, Lee and Whang, 1999, Cachon and Lariviere, 2005, Gerchak and Wang, 2004, Davis and Spekman, 2004, Yao and Chiou, 2004, Chang et al., 2008 among others) have examined theoretical, as well as practical, issues involving buyer-supplier coordination. The research findings claim that well coordinated supply chains have the potential for companies competing in a global market to gain a competitive advantage, especially in situations involving outsourcing, which is becoming increasingly common.

The current chapter discusses, from the perspective of supplier base integration, supply chain coordination for a make-to-order environment in which manufacturing (or assembly) and shipping capacity is ready. The managers have purchase orders in hand and the choice of flexible production and delivery policies in filling the order. For the benefits of operational efficiency, the supplier adopts the policy of frequent shipments of manufactured parts and products in small lots. In the case of standard-size container shipping, each container has limited space, and the manufacturer should split the orders into multiple containers over time. This can be extended to the situation where the manufacturer may have to use multiple companies (different trucks) to ship the entire orders. For the buyer, it is important to work closely with the supplier to facilitate frequent delivery schedules so that the supplier is able to meet the buyer's requirements while still remaining economically viable. Obviously, this collaboration is an example of vendor managed inventory (VMI) system that requires well-managed cooperation between buyer and supplier in terms of sharing information on demand and inventory. While using the multiple delivery models, it is assumed that the vendor has the flexibility to select its own production policy. It can produce all units in a single setup or multiple setups to respond to a buyer's order. The existing literature, however, has not focused on comparisons between single-setup-multiple-delivery (SSMD) and multiple-setup-multiple-delivery (MSMD) policies. Although the SSMD policy is well accepted and gaining popularity, the MSMD policy has been largely disregarded due to the likelihood of high setup costs. However, when we factor in setup reduction through learning and the reduction of necessary inventory space, the MSMD may be just as viable, or even the better option in certain situations. For example, suppose in a make-to-order environment that the supplier receives customer orders frequently through the Internet and has cost/time efficient setup operation, then it is natural for the supplier to choose the MSMD policy over the SSMD policy, since the MSMD policy would help the company keep a low inventory and provide fast delivery to its customers, obviously enhancing the supplier's competitive advantage. This advantage will be apparent especially for the companies in high tech industries, where the product's life cycle tends to be shorter. This is also true of companies in the food industry, where the demand is always for fresh products. See David Blanchard, 2007 for more examples.

In this study, we extend the models that focused on the supplier's production policy (See Kim et al., 2008, and Kim and Ha, 2003). Kim et al., 2008 assumed in their MSMD model that the setup reduction through learning is restricted to one single lot and the learning starts anew for the next lot. In our first extension, however, we relax that assumption and allow that the setup reduction through learning is continued and accumulated throughout the subsequent production lots. The second extension of the model is that the MSMD model is allowed to have unequal setups and deliveries, while retaining the assumption of the MSMD model that the learning on setup reduction is confined to each lot alone and does not continue across lots. In other words, the model allows the number of setups to be unequal to the number of deliveries in each lot. This model may provide greater flexibility to the supplier in determining the production policy compared to the MSMD model or the SSMD model. Numerical examples are presented for illustration.

Although our goal is to elaborate on the entire supply chain synchronization, our discussion is limited to a relatively simple situation, i.e., single buyer and single supplier, under deterministic conditions for a single product that may account for a significant portion of the firm's inventory expenses. It is hoped that the result can be extended to a supply chain where multiple products and multiple parties are involved. In the following sections, the chapter discusses the supply chain coordination issue, from the perspective of supplier base integration, for a make-to-order environment in which manufacturing (or assembly) and shipping capacity is ready. The supplier has the flexibility to select its own production policy, producing all units of demand in either a single setup or multiple setups to respond to a buyer's order, and also to choose a shipping policy of single or multiple deliveries for a given lot. Not much research in the existing literature has focused on comparisons between single-setup-multiple-delivery (SSMD) and multiple-setup-multiple-delivery (MSMD) policies. This study compares the SSMD and the MSMD policies, where frequent setups give rise to learning in the supplier's setup operation. A multiple delivery policy shows a strong and consistent cost-reducing effect on both the buyer and the supplier, in comparison to the traditional lot-for-lot approach. This paper extends the MSMD model in two directions: (1) Modified MSMD Model (I): multiple-setup-multiple-delivery with allowance for unequal number of setups and deliveries, and (2) Modified MSMD Model (II): multiple-setup-multiple-delivery with allowance for cumulative learning on setups over the subsequent production cycles. Numerical illustrations are provided to compare the performance of the proposed models. The concluding section summarizes and discusses the implications of the results obtained.

2. Assumptions of the models and notation

When the buyer orders a quantity, *Q*, the supplier in response can pursue one of the following three policies: (1) Lot for Lot, i.e., single-setup-single-delivery (SSSD), (2) SSMD, or (3) MSMD. In the latter two cases, the order quantity, *Q*, will be split into a smaller delivery size over multiple deliveries, while the setup frequency for each policy would be different. If the setup cost is relatively high, a less frequent setup may be economically attractive to the supplier. The supplier would prefer to produce the entire order quantity, *Q*, with one setup, unless it can reduce the setup cost significantly to justify multiple setups. In this SSMD case, the supplier will hold and maintain the buyer's inventory due to the small delivery lot size. And because the supplier has all the necessary information, he often assumes the role of a central decision-maker in a vendor-managed inventory system. The supplier's cost function includes a setup and order handling cost, and a holding cost, while the buyer's relevant costs consist of an ordering cost, a variable holding cost, and a fixed transportation cost. However, it is not unusual for the buyer to pay increased order handling costs because it is incurred as a result of frequent deliveries imposed by the buyer.

If the MSMD policy is chosen, on the other hand, the supplier can meet the buyer’s demand with lower inventories than in the case of the SSMD policy. But he will incur higher setup costs due to more frequent setups. Also, there will be opportunity costs for the supplier that account for the capacity foregone by having more frequent setups than with the SSMD policy for a given order quantity. However, the MSMD policy may give rise to learning effects on setup operations, which in turn will reduce setup time and cost. The reduced setup time (and cost) will eventually benefit the supplier in the long run. It is reasonable for the buyer and the supplier to share this opportunity cost, because both the buyer and supplier can benefit from such a policy: the supplier achieves setup reduction via the learning effect on setup operations, and the buyer receives the benefits of multiple deliveries, i.e., lower inventories.

Once a long-term contract between buyer and supplier is agreed upon, both parties work in a cooperative manner to coordinate supply with actual customer demand. Their effective linkage in this manner will eventually make any practice of frequent delivery in small lot sizes beneficial to both parties. In this study, market demand rate, production rate, and delivery time are assumed to be constant and deterministic. It is also assumed that all cost parameters, including unit price, are known and constant, and neither quantity-discount nor backorders are allowed. The following notations are adopted:

A = the ordering cost per order for buyer,
a = a parameter associated with supplier's hourly opportunity cost,
b = a parameter associated with decreasing rate of setup time, $-\ln r / \ln 2$ where r represents the percentage learning rate for the supplier’s setup operations,
C = the supplier's hourly setup cost,
D = the annual demand rate for buyer,
F = the fixed transportation cost per delivery trip,
H_B = the holding cost/unit/year for buyer,

H_S = the holding cost/unit/year for supplier, $H_B > H_S$
J = the number of supplier setups per customer lot order, $J = 1, 2, 3, \ldots, N$,
K = the supplier's hourly opportunity cost for the time foregone attributed to the increased number of setups,
N = the number of deliveries per production cycle,
P = the annual production rate for supplier, $P > D$,
Q = the order quantity for buyer,
q = the delivery lot size per trip, $q = Q/N$,
S = the setup time/setup for supplier,
V = the unit variable cost for order handling and receiving,
α = the proportion of the fixed part of the total setup cost,
m = the number of deliveries per setup within a production cycle.

3. Single-Setup-Multiple-Delivery (SSMD) model

In the SSMD model, the order quantity is produced with one setup and shipped through multiple deliveries over time. The multiple deliveries are to be arranged in such a way that each succeeding delivery arrives at the time that all inventories from the previous delivery have just been depleted. As mentioned earlier, the buyer's total cost consists of ordering and holding costs, as well as transportation costs, incurred during the multiple deliveries as:

$$TC(Q,N)_{Buyer} = \frac{D}{Q}A + \frac{Q}{2N}H_B + \frac{DN}{Q}(F + V\frac{Q}{N}) \quad (1)$$

And the supplier's cost function includes a setup and order handling cost, and a holding cost:

$$TC(Q,N)_{Supplier} = \frac{D}{Q}CS + \frac{QH_S}{2N}\left\{(2-N)\frac{D}{P} + N - 1\right\} \quad (2)$$

The aggregate total cost function for both parties is as follows:
Note that $N = 1$ reduces Equations (1) – (3) to the conventional single delivery case, which is a special case of the SSMD

$$TC(Q,N)_{Aggregate} = \frac{D}{Q}(A + CS) + \frac{Q}{2N}\left[H_B + H_S\left\{(2-N)\frac{D}{P} + N - 1\right\}\right] + \frac{DN}{Q}(F + V\frac{Q}{N}) \quad (3)$$

policy. The fact that the second derivatives of Equation (3) (with respect to Q and N) are positive confirms the convexity of the aggregated total cost function. The optimal contract quantity, delivery frequency, and delivery size are as follows:

$$Q^*_{SSMD} = \sqrt{\frac{2D(A+CS)}{H_S(1-\frac{D}{P})}}$$

$$N^* = \sqrt{\frac{(A+CS)\{P(H_B - H_S) + 2DH_S\}}{F(P-D)H_S}}$$

$$q^{*} = \sqrt{\frac{2DFP}{P(H_B - H_S) + 2DH_S}} \tag{4}$$

The expression for optimal order (contract) quantity for SSMD is almost identical to the supplier's independent Economic Production Quantity (EPQ) model, except that the buyer's ordering cost, A, is added to the supplier's setup cost in the numerator of Equation (4). In the SSMD model, the buyer's holding costs and transportation costs do not affect the contract quantity. In other words, the supplier can determine the contract quantity alone without the knowledge of the buyer's holding and transportation costs information. In fact, the integrated optimal order quantity in Equation (4) is greater than the supplier's independent production quantity by the ratio of $\sqrt{(1+\frac{A}{CS})}$, which is close to 1 when the buyer's order cost, A, is very low compared to the supplier's setup cost, CS, as the case may be in current applications of electronic data interchange (EDI) based ordering systems in JIT environments. This is one of the reasons why the supplier may be willing to take a leading role in establishing such supplier-buyer linkage. The optimal delivery size is obtained by dividing the order quantity by the number of deliveries in Equation (4). Kim and Ha, 2003 claimed that the SSMD policy consistently outperforms the single delivery policy, given that the order quantity is greater than the minimum required level.

4. Multiple-Setup-Multiple-Delivery (MSMD) model

In the SSMD model, as shown in the earlier section, the supplier maintains large inventories and incurs high inventory holding costs due to the small delivery lot sizes over the multiple shipments. If the supplier, however, chooses the MSMD policy to set up the production process more frequently and to produce the exact quantity to be shipped on every setup, it can meet the buyer's demand with lower average inventory than in the case of the SSMD policy. But the supplier in this MSMD case consumes more capacity hours due to frequent setups, which incurs higher setup costs in the long run. However, if the supplier's capacity is greater than the threshold level ($P = 2D$), it is more beneficial for the supplier to implement the MSMD policy, even though he pays more frequent setup costs since the savings in inventory holding costs is greater than the increased setup costs. The supplier who has a tight constraint on capacity, therefore, should not choose the MSMD policy until its capacity is expanded. If the supplier has no constraint on capacity, or the savings earned from the lowered inventories compensate for the opportunity costs of the foregone capacity, the MSMD policy would be a feasible option to implement. One other factor pertaining to the MSMD policy is that the MSMD policy results in an increased opportunity to achieve larger learning effects on setup operations, which, in turn, will reduce the setup time/cost. In the following, we develop the structure of the MSMD policy and compare it with the SSMD policy in order to help the decision maker choose the appropriate policy for a given supply chain environment.

We now assume that the system has no constraint on capacity for setting up N batches to produce the order quantity, i.e., the order quantity, Q, is equally split, manufactured and delivered over N times. Learning effects on setup operations is also assumed to reduce the setup time/cost per setup, as the number of setups increases. The MSMD policy obviously changes the supplier's cost structure significantly, but the buyer's total cost remains intact as in Equation (1). The supplier's total cost consists of the setup cost that reflects learning effects due to multiple setups, the holding cost, and the opportunity cost that accounts for the extra setups in the supplier's capacity. The following equation shows these costs in order:

$$TC(Q,N)_{Supplier} = CS\left\{\alpha\frac{D}{Q}N + (1-\alpha)\sum_{J=1}^{DN/Q} J^{-b}\right\} + \frac{QH_S}{2N}\frac{D}{P} + K\left\{e^{a(N-1)} - 1\right\} S\left\{\alpha\frac{D}{Q}(N-1) + (1-\alpha)\sum_{J=\frac{D}{Q}+1}^{DN/Q} J^{-b}\right\}, \quad N \geq 2. \tag{5}$$

In Equation (5) above, α is the fixed cost portion of the setup cost. The setup cost has two components: fixed (or machine) and variable (or human) setup operation. And the learning effect is applied to the variable setup cost only. Without multiple setups, i.e., if *N=1*, Equation (5) reduces to the conventional single delivery lot-for-lot model. The second term in Equation (5) depicts the holding costs, and the third term represents the opportunity cost for the capacity foregone due to increased setups. Frequent setups are more likely to disrupt the supplier's current production schedule and thus there would be opportunity costs for the capacity foregone by having more frequent setups than an SSMD policy. As the number of setups, *N*, increases, the supplier's current opportunity cost per unit time, *K*, also increases. This increasing pattern can be modeled by one of various possible functions, such as linear or exponential, depending upon the supplier's situation of capacity available. If a vendor operates a tight production schedule, the initial opportunity cost *(K)* and the increasing rate of cost per unit of time will be higher than those of other vendors with a less tight schedule. In this paper, the unit time opportunity cost is assumed to be exponentially increasing as shown in the first part of the last term of Equation (5). The second part of the term, which reflects learning effects, is the amount of the supplier's capacity used up for increased number of setups. The entire term then represents the opportunity cost per unit of time. Note that this opportunity cost term vanishes when *N*=1.
The integrated total cost function for both parties is as shown below:

$$TC(Q,N)_{Aggregate} = \frac{D}{Q}A + CS\left\{\alpha\frac{D}{Q}N + (1-\alpha)\sum_{J=1}^{DN/Q} J^{-b}\right\} + \frac{Q}{2N}\left(H_B + H_S\frac{D}{P}\right) + \frac{DN}{Q}\left(F + V\frac{Q}{N}\right) + K\left\{e^{a(N-1)} - 1\right\} S\left\{\alpha\frac{D}{Q}(N-1) + (1-\alpha)\sum_{J=\frac{D}{Q}+1}^{DN/Q} J^{-b}\right\}, \quad N \geq 2, \tag{6}$$

Since the terms reflecting learning effects in Equation (6) bring step functions into the equation, derivatives with respect to *Q* and *N* do not exist at the boundary points of each *J*. Therefore we approximate Equation (6) by a continuous function, i.e.,

$$TC(Q,N)_{Aggregate} \cong \frac{D}{Q}A + CS\left\{\alpha\frac{D}{Q}N + (1-\alpha)\int_{J=0.5}^{\frac{D}{Q}N+0.5} J^{-b}dJ\right\} + \frac{Q}{2N}\left(H_B + H_S\frac{D}{P}\right) + \frac{DN}{Q}\left(F + V\frac{Q}{N}\right) + K\left\{e^{a(N-1)} - 1\right\}S\left\{\alpha\frac{D}{Q}(N-1) + (1-\alpha)\int_{J=\frac{D}{Q}+0.5}^{\frac{D}{Q}N+0.5} J^{-b}dJ\right\}, \quad N \geq 2, \tag{7}$$

Integration for J in Equation (7) leads to

$$TC(Q,N)_{Aggregate} = \frac{D}{Q}A + CS\left[\alpha\frac{D}{Q}N + \frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}N + 0.5\right)^{1-b} - 0.5^{1-b}\right\}\right] + \frac{Q}{2N}\left(H_B + H_S\frac{D}{P}\right) + \frac{DN}{Q}\left(F + V\frac{Q}{N}\right) + K\left\{e^{a(N-1)} - 1\right\}S\left[\alpha\frac{D}{Q}(N-1) + \frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}N + 0.5\right)^{1-b} - \left(\frac{D}{Q} + 0.5\right)^{1-b}\right\}\right]. \tag{8}$$

If the MSMD policy is chosen, the supplier can meet the buyer's demand with lower inventories than in the case of the SSMD policy, although more frequent setups will incur higher setup costs. A comparison of the integrated total costs for both SSMD and MSMD policies in Equations (3) and (8) would be sufficient in leading the supplier to an informed decision. However, since it is difficult to make an algebraic comparison of the two total costs due to the complexities of the expressions, Kim et al., 2008 suggested a brief guideline to help the supplier in making a decision about setup and delivery policy: If the supplier's capacity is greater than the threshold level ($P = 2D$), it is more beneficial for the supplier to implement the MSMD policy and to maintain fewer inventories. Even though the supplier pays greater costs for the frequent setups compared to the SSMD policy, the savings in inventory holding costs surpasses the increased setup costs. As the supplier's production capacity increases, MSMD becomes more and more cost effective. On the other hand, the smaller the supplier's production capacity, the more beneficial SSMD becomes. When we take the learning effect on setup operation into our consideration, as the learning rate on setup operation increases, the rate at which MSMD becomes more efficient accelerates. In the next two subsections, we discuss the extensions of the MSMD model.

4.1 Modified MSMD model (I): Unequal number of setups and deliveries

In this section, we develop a modified multiple setup multiple delivery model (modified MSMD Model (I)), which retains the assumption that the setup reduction through learning is confined to each lot alone and does not continue across lots. However, the modified MSMD model (I) proposed in this section allows the number of setups to be unequal to the number of deliveries in each lot. This model may provide greater flexibility to the supplier in determining the production and delivery policy compared to the MSMD model. For certain parameter values, this modified MSMD model (I) will result in lower total cost compared to the MSMD model. In our modified MSMD model (I) with unequal setups and deliveries, the total cost function takes the following form:

$$TC(Q,m,N)_{Aggregate} = \frac{D}{Q}A + CS\left[\alpha\frac{D}{Q}\left(\frac{N}{m}\right) + \frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}\left(\frac{N}{m}\right)+0.5\right)^{1-b} - 0.5^{1-b}\right\}\right] + \frac{Q}{2N}(H_B)$$
$$+ \left(\frac{\mathrm{N}}{\mathrm{m}}\right)\frac{Q}{2m}H_S\left\{(2-m)\frac{D}{P}+m-1\right\} + \frac{DN}{Q}\left(F+V\frac{Q}{N}\right) \quad (9)$$
$$+K\left\{e^{a(N/m-1)}-1\right\}S\left[\alpha\frac{D}{Q}\left(\frac{N}{m}-1\right)+\frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}\left(\frac{N}{m}\right)+0.5\right)^{1-b} - \left(\frac{D}{Q}+0.5\right)^{1-b}\right\}\right].$$

In this modified MSMD model (I), m is the number of deliveries per setup within a production cycle. The aggregate total cost is comprised of the ordering cost, the setup cost, the inventory cost for both the supplier and the buyer, transportation cost, and the opportunity cost owing to additional setups within the production cycle. The frequency of setups within a production cycle is defined in this model as the ratio of the total number of deliveries to the number of deliveries per setup in a production cycle. The model is formulated as a mixed integer nonlinear programming problem with the objective to minimize the total cost and determine the optimal production batch quantity (Q), optimal number of deliveries (m) per setup, and optimal number of deliveries (N) per production cycle. The constraints for the model are that all three variables Q, m, and N are greater than 0, that N is an integer, and that the number of orders in the finite planning period times the optimal order quantity per batch equals the demand for that finite planning period. The production batch quantity is less than or equal to the demand during the finite planning period, and frequency of setups within a production cycle is greater than 0. The mathematical formulation of the mixed integer nonlinear programming problem for the proposed model is formulated below:

Minimize:

$$TC(Q,m,N)_{Aggregate} = \frac{D}{Q}A + CS\left[\alpha\frac{D}{Q}\left(\frac{N}{m}\right) + \frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}\left(\frac{N}{m}\right)+0.5\right)^{1-b} - 0.5^{1-b}\right\}\right] + \frac{Q}{2N}(H_B)$$
$$+ \left(\frac{\mathrm{N}}{\mathrm{m}}\right)\frac{Q}{2m}H_S\left\{(2-m)\frac{D}{P}+m-1\right\} + \frac{DN}{Q}\left(F+V\frac{Q}{N}\right) \quad (10)$$
$$+K\left\{e^{a(N/m-1)}-1\right\}S\left[\alpha\frac{D}{Q}\left(\frac{N}{m}-1\right)+\frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}\left(\frac{N}{m}\right)+0.5\right)^{1-b} - \left(\frac{D}{Q}+0.5\right)^{1-b}\right\}\right].$$

Subject to:

Q, m, N > 0,

N and m are integers,

$\left(\frac{D}{Q}\right)Q = D,$

Q $\leq$ D,

$$\left(\frac{N}{m}\right) \geq 1.$$

4.2 Modified MSMD model (II): Cumulative learning on setups over production cycles

In this section, we propose another extension of the MSMD model, which allows the learning of setup reduction achieved through earlier operations to accumulate across production cycles throughout the entire planning period. When this is imposed on the modified MSMD model (I), the model becomes modified MSMD model (II), which has the dual properties of both the SSMD and the MSMD models. This model can be applied to the situation where the time interval between consecutive orders is short enough for the supplier not to lose the learning gained from earlier setup operations. The model is thus built along the lines of single setup multiple deliveries with learning on setups over the multiple cycles. The benefits of this model over the MSMD model may be twofold: First, the overall setup cost and, in turn, the total cost is lower compared to the MSMD model. Second, the opportunity cost component incurred owing to additional setups in the MSMD model can be eliminated since the setup times are reduced as the production cycle is repeated. This, in turn, increases the scope for further reduction in the total cost for the same parameter values compared to the MSMD model. The total cost function takes the following form:

$$\begin{aligned} TC(Q,N)_{Aggregate} = \frac{D}{Q}A + CS\left[\alpha\frac{D}{Q} + \frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}+0.5\right)^{1-b} - 0.5^{1-b}\right\}\right] \\ + \frac{Q}{2N}H_B + \frac{QH_S}{2N}\left((2-N)\frac{D}{P}+N-1\right) + \frac{DN}{Q}\left(F+V\frac{Q}{N}\right) \end{aligned} \tag{11}$$

In this model, the total cost is comprised, as shown above, of the ordering cost, the setup cost that reduces through learning for subsequent setups during the entire finite planning period, the inventory cost of the buyer and the supplier, and the transportation cost, which is comprised of the fixed and the variable transportation cost components. The model is built along the lines of the single setup multiple delivery models with the addition of the variable N, the number of shipments from the supplier to the buyer in each setup. Owing to multiple shipments during each production lot, the supplier's inventory cost function is similar to the one obtained by Kim and Ha (2003).

The modified MSMD model (II) can be formulated as a mixed integer nonlinear programming problem with the objective to minimize the total cost as shown below:

Minimize:

$$\begin{aligned} TC(Q,N)_{Aggregate} = \frac{D}{Q}A + CS\left[\alpha\frac{D}{Q} + \frac{(1-\alpha)}{(1-b)}\left\{\left(\frac{D}{Q}+0.5\right)^{1-b} - 0.5^{1-b}\right\}\right] \\ + \frac{Q}{2N}H_B + \frac{QH_S}{2N}\left((2-N)\frac{D}{P}+N-1\right) + \frac{DN}{Q}\left(F+V\frac{Q}{N}\right) \end{aligned} \tag{12}$$

Subject to:

$$\left(\frac{D}{Q}\right)Q = D.$$

The variables to be determined are the production batch quantity Q and the number of shipments N in order to determine the supplier's production and delivery policy at the minimal total cost for the supply chain.

5. Numerical illustration

Suppose a buyer, who is currently using an *EOQ* policy seeking short-term advantage, plans to develop a long-term buyer-vendor relationship for an improved supply chain management. The buyer's annual demand is *D = 4,800 units/year*, ordering cost is *A = $25/order*, and holding cost is H_B = *$5/unit/year*. The fixed cost per trip and unit variable transportation costs are *F = $50.00* and *V = $1.00/unit*, respectively. For our illustration purposes, we consider that the supplier's annual production capacity can be any level of the following: 9,600 units, 19,200 units, 28,800 units, 38,400 units, and 48,000 units. Depending upon the supplier's selected capacity level, the supplier may use from 50% to 10% of its capacity to meet the buyer's demand. The unit holding cost for the supplier, H_S = $4/unit/year. It currently takes 5 workers 6 hours to set up the system, and the hourly labor cost per worker is $20. Thus, the cost per setup is *$600 ($20/hr × 5 worker × 6 hrs.)*. And the fixed cost portion of the setup cost (α) is 0.5. The learning rates (*r*) considered in this example are 90% (*b* = 0.152003), 80% (*b* = 0.321928), and 70% (*b* = 0.514573). The parameter value associated with the supplier's hourly opportunity cost (a) is 0.003. Tables 2 through 16 illustrate 15 different scenarios, in which only the production rate (*P*) and the learning rate (*r*) vary while other parameters remain unchanged. Notice that the parameter (*b*), which is associated with the learning rate, varies as the learning rate varies.

D = 4,800 units/year	H_S = $4 per unit per year
A = $25 per order	**P = 9,600 units/year**
H_B = $5 per unit per year	a = 0.003
F = $50 per shipment	**r = 90%**
V = $1 per unit	**b = 0.152003**
C = $100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 2. (P = 9,600, r = 90%, b = 0.152003)

D = 4,800 units/year	H_S = $4 per unit per year
A = $25 per order	**P = 9,600 units/year**
H_B = $5 per unit per year	a = 0.003
F = $50 per shipment	**r = 80%**
V = $1 per unit	**b = 0.321928**
C = $100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 3. (P = 9,600, r = 80%, b = 0.321928)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 9,600 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 70%**
V = \$1 per unit	**b = 0.514573**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 4. (P = 9,600, r = 70%, b = 0.514573)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 19,200 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 90%**
V = \$1 per unit	**b = 0.152003**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 5. (P = 19,200, r = 90%, b = 0.152003)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 19,200 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 80%**
V = \$1 per unit	**b = 0.321928**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 6. (P = 19,200, r = 80%, b = 0.321928)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 19,200 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 70%**
V = \$1 per unit	**b = 0.514573**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 7. (P = 19,200, r = 70%, b = 0.514573)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 28,800 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 90%**
V = \$1 per unit	**b = 0.152003**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 8. (P = 28,800, r = 90%, b = 0.152003)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 28,800 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 80%**
V = \$1 per unit	**b = 0.321928**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 9. (P = 28,800, r = 80%, b = 0.321928)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 28,800 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 70%**
V = \$1 per unit	**b = 0.514573**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 10. (P = 28,800, r = 70%, b = 0.514573)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 38,400 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 90%**
V = \$1 per unit	**b = 0.152003**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 11. (P = 38,400, r = 90%, b = 0.152003)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 38,400 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 80%**
V = \$1 per unit	**b = 0.321928**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 12. (P = 38,400, r = 80%, b = 0.321928)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 38,400 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 70%**
V = \$1 per unit	**b = 0.514573**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 13. (P = 38,400, r = 70%, b = 0.514573)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 48,000 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 90%**
V = \$1 per unit	**b = 0.152003**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 14. (P = 48,000, r = 90%, b = 0.152003)

D = 4,800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 48,000 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 80%**
V = \$1 per unit	**b = 0.321928**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 15. (P = 48,000, r = 80%, b = 0.321928)

D = 4800 units/year	H_S = \$4 per unit per year
A = \$25 per order	**P = 48000 units/year**
H_B = \$5 per unit per year	a = 0.003
F = \$50 per shipment	**r = 70%**
V = \$1 per unit	**b = 0.514573**
C = \$100 per hour	K = 100
S = 6 hours per setup	α = 0.5

Table 16. (P = 48,000, r = 70%, b = 0.514573)

We coded the models as mixed integer nonlinear programming problems in AMPL language and solved them using the MINLP solver on the Neos solver website (http://www.neos-server.org/neos/solvers/minco:MINLP/AMPL.html). Tables 17 through 31 provided are the results obtained for each scenario presented in tables 2 through 16 respectively. For example, Table 17 contains the result of the parameter values in Table 2 for the 5 different models, namely Lot-for-Lot, SSMD, MSMD, Modified MSMD (I), and Modified MSMD (II). The metrics used for each model are aggregate TC per year, *Q**, *N**, *D/Q**, *m**, and *N*/m**. The *D/Q** gives the frequency of orders per year, while *N*/m** gives the frequency of setups per order (when applicable).

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) \$ per year	\$11,535.00	\$9,816.00	\$11,107.00	\$9,678.57	\$9,678.57
Q*	962	1770.34	853.33	1569.76	1569.76
N*	N/A	6	1	5	5
D/Q*	5	2.71	5.62	3.06	3.06
m*	N/A	N/A	N/A	5	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 17. (Result of Table 2)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) \$ per year	\$11,535.00	\$9,816.00	\$10,633.14	\$9,525.09	\$9,525.09
Q*	962	1770.34	737.3	1460.36	1460.36
N*	N/A	6	1	5	5
D/Q*	5	2.71	6.51	3.29	3.29
m*	N/A	N/A	N/A	5	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 18. (Result of Table 3)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$11,535.00	$9,816.00	$10,115.00	$9,333.90	$9,333.90
Q*	962	1770.34	618.08	1221.23	1221.23
N*	N/A	6	1	4	4
D/Q*	5	2.71	7.76	3.93	3.93
m*	N/A	N/A	N/A	4	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 19. (Result of Table 4)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$11,035.38	$10,249.77	$10,662.91	$10,036.27	$10,036.27
Q*	1039.23	1453.27	926.21	1254.36	1254.36
N*	N/A	4	1	3	3
D/Q*	4.62	3.30	5.18	3.83	3.83
m*	N/A	N/A	N/A	3	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 20. (Result of Table 5)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$11,035.38	$10,249.77	$10,248.29	$9,796.28	$9,796.28
Q*	1039.23	1453.27	804.82	1138.27	1138.27
N*	N/A	4	1	3	3
D/Q*	4.62	3.30	5.96	4.22	4.22
m*	N/A	N/A	N/A	3	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 21. (Result of Table 6)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$11,035.38	$10,249.77	$9,791.52	$9,521.93	$9,521.93
Q*	1039.23	1453.27	678.657	883.795	883.795
N*	N/A	4	1	2	2
D/Q*	4.62	3.30	7.07	5.43	5.43
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 22. (Result of Table 7)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,859.7	$10,330.52	$10,506.20	$10,105.46	$10,105.46
Q*	1069.36	1345.26	954.78	1236.42	1236.42
N*	N/A	3	1	3	3
D/Q*	4.49	3.57	5.03	3.88	3.88
m*	N/A	N/A	N/A	3	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 23. (Result of Table 8)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,859.70	$10,330.52	$10,111.98	$9,840.35	$9,840.35
Q*	1069.36	1345.26	831.4	1009.21	1009.21
N*	N/A	3	1	2	2
D/Q*	4.49	3.57	5.77	4.76	4.76
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 24. (Result of Table 9)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,859.70	$10,330.52	$9,676.44	$9,521.93	$9,521.93
Q*	1069.36	1345.26	702.62	883.795	883.795
N*	N/A	3	1	2	2
D/Q*	4.49	3.57	6.83	5.43	5.43
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 25. (Result of Table 9)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,771.34	$10,367.18	$10,427.27	$10,132.32	$10,132.32
Q*	1085.18	1336.4	969.8	1130.33	1130.33
N*	N/A	3	1	2	2
D/Q*	4.42	3.59	4.95	4.25	4.25
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 26. (Result of Table 10)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,771.34	$10,367.18	$10,043.21	$9,840.35	$9,840.35
Q*	1085.18	1336.4	845.39	1009.21	1009.21
N*	N/A	3	1	2	2
D/Q*	4.42	3.59	5.68	4.76	4.76
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 27. (Result of Table 11)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,771.34	$10,367.18	$9,618.30	$9,521.93	$9,521.93
Q*	1085.18	1336.4	715.27	883.795	883.795
N*	N/A	3	1	2	2
D/Q*	4.42	3.59	6.71	5.43	5.43
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 28. (Result of Table 12)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,715.40	$10,396.43	$10,377.26	$10,132.32	$10,132.32
Q*	1095.45	1243.65	979.55	1130.33	1130.33
N*	N/A	2	1	2	2
D/Q*	4.38	3.86	4.9	4.25	4.25
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 29. (Result of Table 13)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,715.40	$10,396.43	$9,999.60	$9,840.35	$9,840.35
Q*	1095.45	1243.65	854.49	1009.21	1009.21
N*	N/A	2	1	2	2
D/Q*	4.38	3.86	5.62	4.76	4.76
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 30. (Result of Table 14)

	Lot for Lot	SSMD	MSMD	Modified MSMD (I)	Modified MSMD (II)
TC(Aggregate) $ per year	$10,715.40	$10,396.43	$9,581.39	$9,521.93	$9,521.93
Q*	1095.45	1243.65	723.49	883.795	883.795
N*	N/A	2	1	2	2
D/Q*	4.38	3.86	6.63	5.43	5.43
m*	N/A	N/A	N/A	2	N/A
N*/m*	N/A	N/A	N/A	1	N/A

Table 31. (Result of Table 15)

We compare the results for the 5 models in the context of annual $TC_{Aggregate}$ in Table 1 based on the data obtained from Tables 17 through 31 for the 15 different sets of parameter constants.

Serial #, P, r %	**Lot-4-Lot ($)**	**SSMD ($)**	**MSMD ($)**	**Modified ($) MSMD (I)**	**Modified ($) MSMD (II)**
1. 9600, 90%	$11,535.00	$9,816.00	$11,107.00	$9,678.57	$9,678.57
2. 9600, 80%	11,535.00	9,816.00	10,633.14	9,525.09	9,525.09
3. 9600, 70%	11,535.00	9,816.00	10,115.00	9,333.90	9,333.90
4. 19200, 90%	11,035.38	10,249.77	10,662.91	10,036.27	10,036.27
5. 19200, 80%	11,035.38	10,249.77	10,248.29	9,796.28	9,796.28
6. 19200, 70%	11,035.38	10,249.77	9,791.52	9,521.93	9,521.93
7. 28800, 90%	10,859.70	10,330.52	10,506.20	10,105.46	10,105.46
8. 28800, 80%	10,859.70	10,330.52	10,111.98	9,840.35	9,840.35
9. 28800, 70%	10,859.70	10,330.52	9,676.44	9,521.93	9,521.93
10. 38400, 90%	10,771.34	10,367.18	10,427.27	10,132.32	10,132.32
11. 38400, 80%	10,771.34	10,367.18	10,043.21	9,840.35	9,840.35
12. 38400, 70%	10,771.34	10,367.18	9,618.30	9,521.93	9,521.93
13. 48000, 90%	10,715.40	10,396.43	10,377.26	10,132.32	10,132.32
14. 48000, 80%	10,715.40	10,396.43	9,999.60	9,840.35	9,840.35
15, 48000, 70%	10,715.40	10,396.43	9,581.39	9,521.93	9,521.93

Table 1. Comparison of 5 Models

It is observed that in all 15 cases, the SSMD model yields better (lower) TC compared to the Lot-for-Lot model. It is apparent that, as the supplier's production capacity and learning rate increase, the MSMD policy becomes more and more efficient. For a given production capacity level, the performance of the MSMD policy improves as the system retains more learning on setup operations. In other words, the smaller the supplier's production capacity, the more beneficial the SSMD becomes. Throughout all the 15 cases, both the modified MSMD (I) model and modified MSMD (II) consistently outperform the other three models. Due to the specific parameter values, the ratio of N^*/m^* remains the same for all 15 scenarios and there is no difference in performance for the above example between the modified MSMD (I) model and the MSMD (II) model.

6. Conclusion

An effective linkage between the stages (or parties) that form the supply chain, based on a cooperative strategy that strengthens buyer-supplier relationships, improves the competitive position of the entire chain. Through such integration, both buyer and supplier can obtain benefits in terms of quality, flexibility, costs, and reliability of supply, etc. A key goal of supply chain management is therefore the coordination of all the activities from the material suppliers through manufacturer and distributors to the final customers.

In an effort to improve the supply chain coordination, this study compares the single-setup-multiple-delivery (SSMD) and the multiple-setup-multiple-delivery (MSMD) policies, where frequent setups give rise to learning in the supplier's setup operation. The consistency of our results obtained from the SSMD is also observed in a more complex environment, i.e., multiple setups and multiple deliveries. The learning effects in MSMD policy tend to decrease the capacity loss and opportunity cost that may result from more frequent setups. As the learning rate on setup operation increases, the rate at which MSMD becomes more efficient accelerates. This paper extends the MSMD model in two directions: (1) Modified MSMD Model (I): multiple setup multiple delivery with allowance for unequal number of setups and deliveries, and (2) Modified MSMD Model (II): multiple setup multiple delivery with allowance for cumulative learning on setups over the subsequent production cycles. The modified MSMD models showed improved performance in aggregate total costs over the MSMD model throughout the entire finite planning horizon. Overall, the supply chain coordination strategy facilitating multiple setups and multiple deliveries in small lot sizes show a strong and consistent cost-reducing effect, in comparison with the Lot-for-Lot approach, on both the buyer and the supplier. It is suggested that the surplus benefits are shared by both parties according to the contribution (or sacrifice) each party made to the integration efforts.

As a guideline for the supplier in selecting the policy, this study claims that it is more beneficial for the supplier to implement the multiple setups and multiple deliveries (MSMD) policy if the supplier's capacity is greater than the threshold level ($P = 2D$), even though he pays more frequent setup costs, since the savings in inventory holding costs is greater than the increased setup costs. If the supplier has no constraint on capacity, or the savings earned from the lowered inventories compensate for the opportunity costs of the foregone capacity, the MSMD policy would be a feasible option to implement.

For future research purposes, the proposed model may be further embellished to address cases involving multiple buyers, suppliers, and products. Finally, the development of stochastic models in this area is likely to result in a more meaningful, albeit more complex, analysis under real world conditions.

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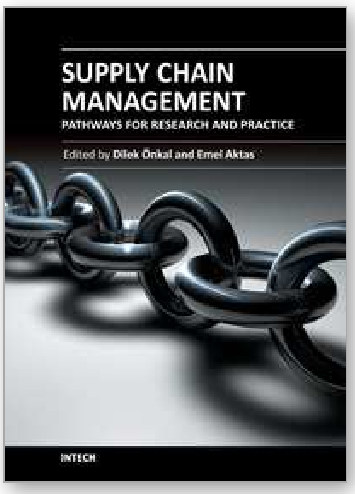

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